1.0 SCIENCE REQUIREMENTS AND MISSION SCIENCE PERFORMANCE

1.1 TRIP Executive Summary

The Constellation-X mission will revolutionize our understanding of the cosmos. Scientists around the world will use its factor of 100 increase in throughput over previous missions to study the warping of space and time by strong gravity near black holes; determine the distribution of the ordinary matter, dark matter, and dark energy that constitute our universe; and probe the detailed physical processes occurring at temperatures, densities, and pressures far beyond those achievable in Earth-bound laboratories.

Constellation-X Starts "Beyond Einstein" Initiative With a Bang

- Science success guaranteed
- Experienced team with world leaders in field
- Broad technology base plus focused technology efforts provide path to flight program
- Modular approach minimizes risk and cost

Constellation-X builds on three decades of X-ray satellites, including the currently operating Chandra X-ray Observatory (NASA) and XMM-Newton mission (ESA), and builds on proven technology. Grazing incidence mirrors with higher angular resolution than Constellation-X have already been built and flown on Chandra, and replication techniques relevant for Constellation-X's large area mirrors have been used to build optics for XMM-Newton and for Japan's Astro-E and Astro-E2 missions. X-ray microcalorimeters have been developed for Astro-E/E2, while reflection gratings are flying on XMM-Newton and X-ray Charge Coupled Devices (CCDs) on Chandra and XMM-Newton. Hard X-ray telescopes with multilayers and cadmium-zinc-telluride detectors have successfully flown on balloons. Our Constellation-X team members have played key roles in all of these missions. Using this experience, our team has undertaken a comprehensive technology program structured to reach Technology Readiness Level (TRL) 6 in all areas before the mission Non-Advocate Review (NAR) scheduled for August 2006. For the Spectroscopy X-ray Telescope (SXT) mirror, whose fabrication represents the project's "tall pole," X-ray tests of an engineering unit are scheduled for early FY 2004.

The technology requirements flow from the mission science objectives, as articulated by the Facility Science Team (FST) composed of approximately 50 scientists from more than 30 different institutions representing essentially all of the groups presently active in the field. The objectives have been vetted and strongly supported in two different major reviews by the National Academy of Sciences (NAS) in 2001 and 2002. The Constellation-X science, management, and engineering teams, led by Goddard Space Flight Center (GSFC) and the Smithsonian Astrophysical Observatory (SAO) and supported by the leads of the Integrated Product Teams (IPTs), have mapped the science objectives to the technology requirements for the mission. The steps needed to achieve TRL 6 and manufacturing readiness for each of the key technologies have been cast into a technology roadmap used to establish schedules and budgets. This approach provides the flow-down, or trace, from the objectives to the requirements and allows the team to identify and carry out system analyses and trades to optimize resource utilization for the technology efforts and more importantly for the implementation phase.

To illustrate the maturity of the architecture and design based on system analyses and engineering already accomplished, we note design decisions from three significant trades. We have baselined four observatories launched in pairs in 2010 and 2011 to build up the required collecting area and reduce impacts of single failures, while keeping costs at an acceptable level. We have chosen segmented mirrors rather than full shells for the SXT, driven primarily by costs and availability of large mandrels for replicating reflectors. We will fly mechanical cryocoolers for the X-ray Microcalorimeter Spectrometer (XMS), along with a multiple-stage Continuous Adiabatic Demagnetization Refrigerator (CADR) to achieve the required operating temperature. This approach provides substantially longer life for the instrument at much lower weight than expendable cryogens and draws from joint technology efforts of other Office of Space Science (OSS) projects, including the James Webb Space Telescope (JWST) and Terrestrial Planet Finder.

The trace from science objectives to requirements provides clear insight into the impact of scope changes. The technology program provides the path from the large base of demonstrated and flight-proven hardware to the needs of the Constellation-X mission. The breadth of experience and the technology roadmap provide an excellent understanding of the program and a basis for sound cost estimates. During the technology phase, we also allow for potential breakthroughs that might provide substantial increases in performance and/or reduce risks and costs. In some cases, we allocate modest amounts of our limited technology budget to evaluate promising possibilities (e.g., increased grating spectral resolution). For others, we are tracking efforts by team members (Italian and German colleagues on optics) or leveraging industry investments to evaluate options (higher SXT mirror angular resolution). The potential performance gain from well-identified goals is illustrated by the Chandra mirrors, where a few extra hours of final smoothing per surface led to a high frequency surface finish of 0.3 nm RMS (goal) as compared to the requirement of 0.7 nm, at essentially no increase in project cost and with substantial reduction in mirror scatter at higher energies.

Multi-Observatory Mission Approach Reduces Cost and Risk

- Four observatories with common design, manufacturing, assembly, and testing
- Manageable mirror dimensions
- Proven spacecraft subsystems and launch vehicles
- Mission success even with loss of one observatory via longer exposures

Constellation-X does not require formation flying or interferometry. All satellites are simply commanded to view the same target, and the data are added together on the ground. Constellation-X baselines a joint operations and science center co-located with the Chandra X-ray Center (CXC) to maximize synergy with the experienced Chandra team and draw upon the extensive and directly relevant software and procedures already in use.

The management approach to Constellation-X is simple. There is a single manager at GSFC who will draw upon the experienced team of GSFC and SAO engineers and scientists as well as the Instrument Principal Investigators selected via a competitive Announcement of Opportunity (AO). The approach is based on the very effective Chandra model. With at most modest contributions from potential international partners and a single prime contractor for the observatories, interfaces will be relatively simple, responsibilities well-defined, and schedules and budgets easily tracked and managed, leading to less risk and easier decision making.

The science gains with Constellation-X will be enormous. Over the past several years, we have identified the required technology and established the roadmap needed to demonstrate feasibility and readiness for mission implementation. Substantial progress has already been made, and achievable plans are in place for the remainder of the formulation and implementation phases. The mission concept is elegant and resilient; the management approach is simple and strong; the technology will be in hand soon. We are ready to proceed.

1.1.1 Foldout Walkthrough

This report includes four foldouts that provide a framework for the text. Foldout 1 is a traceability matrix that traces each science objective to its corresponding science plan, measurement parameters, performance requirements, and then to the subsystem requirements. Foldout 2 centers on mission elements: the spacecraft and location of key instrument systems; the reference spacecraft block diagram; launch and orbit; and the ground segment approach. Foldout 3 focuses on mission optics, while Foldout 4 illustrates mission sensors.

1.2 Science and Mission Requirements

1.2.1 Science Objectives and Derived Science Requirements

The four top-level science objectives of Constellation-X pursue the objectives of NASA's Structure and Evolution of the Universe (SEU) roadmap and extend recent discoveries of Chandra and XMM-Newton. These objectives have been strongly endorsed by the community-at-large as discussed in the 2001 NAS Astronomy and Survey Committee report[1]. Constellation-X also directly addresses several key questions and long-term goals outlined in two recent NAS physics reports[2][3]. The top-level science objectives are presented here, followed by a summary of a subset of the key requirements that flow to the measurement capabilities (summarized in Foldout 1). These requirements (the full set of which can be found in the Top-Level Requirements Document[4]; [TLRD]) are the baseline requirements, and have been approved by the FST. The associated minimum requirements and goals are discussed in Sections 1.2.3 and 1.2.4, and summarized in Table 1-1. In many cases, a mission science requirement may be derived from several science objectives. All science requirements have been refined based on input from leading members of the scientific community, detailing the specific targets and studies that are needed to meet the top-level objectives, via an Observation Design Reference Mission[5] (ODRM). The ODRM will continue to evolve and be used to refine the requirements. The TLRD has remained stable for the last two years, with only minor modifications.

The specific requirements that flow from each of the following science objectives are described in the Flowdown Requirements Document[6] and are given in Foldout 1. While most have been developed to achieve individual science objectives, mission life and data volume result from considering the ensemble of objectives. Observing a statistically-significant number of sources places a joint requirement on effective area and mission duration.

Objective 1: Measure the effects of strong gravity near the event horizon of supermassive black holes.

X-ray spectroscopy–and in particular the detailed variability of the iron K fluorescence emission line near 6 keV–is a powerful probe of the dynamics and space-time geometry within a few gravitational radii of accreting, supermassive black holes in active galactic nuclei (AGN)[7]. Iron K is produced when X-rays illuminate the accreting material that is the fuel for such black holes. CCD-resolution spectra show that the Fe K line carries the imprint of strong general relativity (GR), but they provide inadequate knowledge of the line origin. Constellation-X will probe the effects of strong GR on this, the only spectral feature that is known to originate from close to the black hole. Conceivably, one might observe variability that cannot be understood within the context of GR, requiring possible modifications to Einstein's theory or suggesting the presence of extra fields near the event horizon that alter particle and/or photon dynamics. Very recent Chandra results have shown unanticipated structure in the Fe K region requiring high spectral resolution to interpret. It is only through spectroscopy that one can hope to unfold the relationship between GR and the detailed physics of black holes (such as mass and spin[8]) and their environment.

Studying the effects of GR in extreme environments requires accumulating high signal-to-noise, high-resolution spectra on the dynamical timescales of the innermost stable orbit of the accretion disk (typically of order 1000 seconds for a 10^8 solar mass black hole). To adequately use such spectra also requires determining the full underlying continuum shape, which allows the properties of relativistically broadened emission lines to be measured with high accuracy (Foldout 1-A). These needs require a resolving power of 1,500 near 6 keV and instantaneous collecting areas of 6,000 cm^2 and 1,500 cm^2 at 6 and 40 keV, respectively.

Objective 2: Trace visible matter throughout the universe and constrain the nature of dark matter and dark energy.

Recent results indicate that most of the energy density of the universe exists in the form of dark matter and dark energy[9]. These findings are a major challenge to physics since there is no unique candidate for dark matter and no present physical theory accounts for dark energy. Clusters of galaxies (the largest known gravitationally organized systems) are important probes of dark matter and dark energy, as well as the structure, evolution and mass content of the universe. In addition, X-ray observations of clusters allow us to constrain cosmological parameters such as the rate of expansion of the universe, the fraction of mass in visible (baryonic) matter, and the amplitude of primordial density fluctuations in the universe[10]. Constellation-X will measure the ratio of baryons in clusters to their total mass and will determine with high precision the distribution of dark matter out to z~2 (where these objects are about 1 arcminute in diameter and have relatively high surface brightness). At higher redshifts, integral spectra of clusters and galaxy groups will provide bounds on the dark matter and baryonic distribution.

In the local universe, the observed baryons fall far short of those predicted by standard big bang nucleosynthesis[11]. Numerical simulations predict that most of these "missing" baryons are in a hot intergalactic medium (IGM)[12]. This IGM is detectable through faint X-ray absorption lines imprinted by highly ionized metals on the spectrum of background quasars (Foldout 1-B). To detect these features requires a resolving power of at least 300 at and below 0.6 keV.

To test fundamental models of the evolution of cosmic structure requires knowing how many objects are forming, where they are forming, and how they are distributed. By measuring the change in the number density of clusters with specific masses as a function of redshift, Constellation-X will trace the entire history of large-scale hierarchical cluster formation. Meeting this objective requires a large collecting area near 1 keV and determination of cluster temperatures (thereby deriving masses) and abundances with the necessary 10% accuracy to distinguish between competing cosmological theories[13].

Objective 3: Study the formation of supermassive black holes and trace their evolution with cosmic time.

The faint sources that make up the X-ray background were discovered by Chandra and XMM[14]. Many of these may be highly obscured AGNs, which are a significant contributor to the accretion luminosity of the universe. Constellation-X will investigate the evolution of black holes by determining spin, mass and accretion rate over a wide range of luminosity and redshift (Foldout 1-C).

To resolve a significant fraction of the X-ray background where it peaks in energy density requires avoiding source confusion at flux limits of ~1 x 10^{-15} erg/cm^2/s below 10 keV and ~1 x 10^{-14} erg/cm^2/s above 10 keV. This requires an angular resolution of ~15 arcsec (1 to 10 keV) and ~1 arcmin (10 to 40 keV).

Objective 4: Study the life cycles of matter and energy and understand the behavior of matter in extreme environments.

Spectroscopic observations of stellar coronae, supernova remnants, and the interstellar medium provide information on chemical enrichment processes and will provide plasma temperatures, pressures, densities, and velocities over a wide range of astrophysical settings, allowing a tracing of the all-important life cycle of elements in the universe. Detailed X-ray line spectra are rich in plasma diagnostics from the abundant metals (C through Zn) that provide unambiguous constraints on physical conditions in astrophysical sources (Foldout 1-D).

Millisecond oscillations in X-ray bursts have been identified as due to inhomogeneous nuclear burning on the surfaces of rapidly rotating neutron stars[15]. Spectroscopy of the burst emission will constrain the neutron mass/radius relation, and lead to important constraints on the equation of state of high-density nuclear matter found in neutron stars. Finally, microquasars are known to possess relativistically broadened iron lines and, similar to supermassive black holes in AGN, Constellation-X will be able to study iron line variability and measure mass and spin of stellar-mass black holes.

Obtaining the plasma diagnostics from the abundant metals (C through Zn) places a requirement on the bandpass and spectral resolving power at low energies. Phase-resolved spectroscopy of neutron stars and studies of quasi-periodic oscillations (QPOs) place a requirement on the absolute timing capability.

1.2.2 Investigations

The investigations to be performed to meet the scientific objectives outlined in Section 1.2.1 have been selected from careful studies by members of the Constellation-X FST and Science Panels in response to an internal call for proposals to help define an ODRM. During the mission operations phase of the mission, the project expects to receive proposals representative of all of these investigations, as well as for many other guest investigations that are not yet represented in the ODRM.

Within the four main science objectives, there are at least 14 distinct classes of objects to be studied (Foldout 1).

Achieving the science objectives requires investigation of statistically significant samples of these astrophysical sources–unlike Chandra and XMM-Newton which are restricted to the brightest (and hence not necessarily representative) members of each class. Typical exposure times are expected to run up to 100 ksec. For certain classes and sources, monitoring observations will be required. As an example of the types of observations required to achieve the science objectives, one case is described in detail below. The remaining cases are summarized in Foldout 1.

Detailed studies of the gravitational effects near supermassive black holes will require monitoring observations of the Fe K line variability in about 25 of the brightest AGN. Typical observations will last about 30 ksec (allowing tracking of the line variability on spatial scales ~25 times larger than the innermost

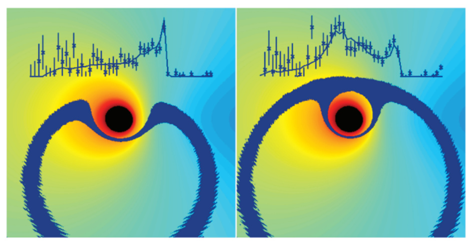
Constellation-X

Traceability Matrix:

Specific objectives have a clear trace to implementation

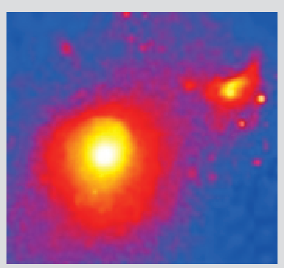
A

Simulated spectra of two iron K fluorescence line profiles in 1,000 s intervals after a flare erupts above an accretion disk (color image). The profiles change as the flare's echo (dark band) propagates toward the black hole.

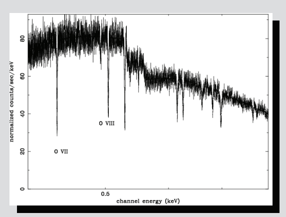


B

A) X-rays from clusters will constrain models of the formation of large-scale structure in the universe.

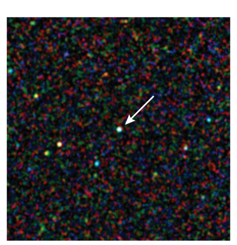


B) Missing baryons in the local universe are detectable via X-ray absorption lines in the spectrum of background quasars.

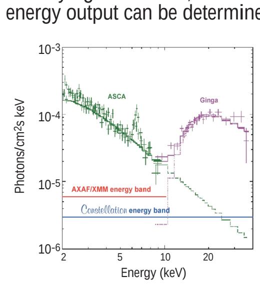


C

A) Constellation-X will obtain high quality spectra of recently discovered sources that make up the X-ray background.

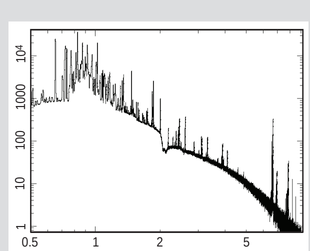


B) By measuring the low-energy (scattered) emission and the underlying continuum, their total energy output can be determined.



D

Spectroscopic observations of stellar coronae, supernova remnants, and the interstellar medium will allow a tracing of the all important life cycle of elements in the universe.



	Science Objectives	Measurement Parameters: Science Topics	Category of Targets	No. Unique Targets	Pointings/ Source	Representative Data Quality	Typ. Texp (ksec)	Total Time (ksec)	Primary Data Type Returned	Performance Requirements Table 1-1: Bandpass	Effective Area	Spectral Resolving Power, R	Imaging	Other	Representative Data Volume (bits)
A	*I. Measure the effects of strong gravity near the event horizon of supermassive black holes*	Study general relativity effects in the presence of extreme gravity	Bright active galactic nuclei (AGN)	30	10	S/N of 50 to 100 in narrow and broad features near 6 keV Constrain continuum >10 keV	30	9,000	Spectra, timing	0.5 to 40 keV	6,000 cm2 instantaneous at 6.0 keV	1,500 at 6.0 keV 10 at 40 keV	Angular resolution of 1 arcmin above 10 keV		6.6×10^8 [bright AGN] example: RGS: 2.9×10^7 XMS: 6.1×10^8 HXT: 1.5×10^7
		Black hole properties	AGN	50	2*	Velocity resolution <100 km/s Spatially separate sources	50	5,000	Spectra	0.5 to 40 keV	1,500 cm2 instantaneous at 40 keV				3.4×10^8 [other AGN]
B	*II. Trace visible matter throughout the universe and constrain the nature of dark matter and dark energy*	Masses, abundances, dark matter, dark energy, cosmology	Galaxy clusters	120	1	Measure abundance and temp. with 10% accuracy	40	4,800	Spectra, images	0.25 to 40 keV	3,000 cm2 at 0.6 keV	300 at 0.6 keV 1,500 at 6.0 keV	Angular resolution of 15 arcsec at 1 keV		8.0×10^7 [nearby cluster]
		Cluster formation models, shocked gas	Galaxy clusters	60	1	Velocity resolution <100 km/s Detect Inverse-Compton hard X-rays	100	6,000	Spectra, images	0.25 to 40 keV	15,000 cm2 at 1.25 keV	10 at 40 keV	FOV of 2.5 arcmin at 1 keV		5.6×10^6 [cluster, z=0.2]
		Masses, abundances, dark matter	Elliptical galaxies and galaxy groups	100	1	Radial temperature profiles	40	4,000	Spectra, images	0.25 to 10 keV	1,500 cm2 at 40 keV				3.0×10^6 [cluster, z=1]
		Find low redshift baryons in the IGM	Low-Z QSOs	20	1	Detect OVII and OVIII absorption near 0.6 keV	500	10,000	Spectra	0.25 to 1 keV			FOV of 8 arc-min at 40 keV		
C	*III. Study the formation of supermassive black holes and trace their evolution with cosmic time*	Properties of Chandra/XMM deep-field sources and the X-ray background	Faint X-ray sources	100 100	1 1	Avoid source confusion at fluxes of ~1 x 10^{-15} erg/cm^2/s below 10 keV and ~1x10^{-14} erg/cm^2/s above 10 keV	50 100	5,000 10,000	Spectra, images	1.0 to 40 keV	15,000 cm2 at 1.25 keV	1,500 at 6.0 keV 300 at 0.6 keV	Angular resolution of 15 arcsec at 6 keV	TOOs: ~1/month	2.4×10^3 [faint AGN] 1.1×10^6 [AGN]
		Black hole evolution	AGN	100	1		50	500	Spectra	0.25 to 40 keV	6,000 cm2 at 6.0 keV	10 at 40 keV	Celestial coordinate accuracy of 5 arcsec		
		Interstellar medium, dark matter, starburst-AGN connection	Spiral and starburst galaxies	60	1	Probe absorbing columns of up to 10^{25} cm^{-2}	40	2,400	Spectra, timing, images	0.25 to 40 keV	1,500 cm2 at 40 keV		Angular resolution of 1 arcmin above 10 keV		2.0×10^8 [galaxy]
D	*IV. Study the life cycles of matter and energy and understand the behavior of matter in extreme environments*	Composition of ISM, nucleosynthesis, life cycle of matter	SNR (maps require many pointings)	30	10**	Spatially resolve SNR ejecta	30	9,000	Images, spectra	0.25 to 10 keV	15,000 cm2 at 1.25 keV	1,500 at 6.0 keV	Angular resolution of 15 arcsec at 1 keV	TOOs: ~1/month	7.4×10^8 [bright SNR]
		Mass function	XRBs	75	1	Velocity resolution <100 km/s	50	3,750	Timing, spectra	0.5 to 10 keV	15,000 cm2 instantaneous at 1.25 keV	300 at 0.6 keV			1.2×10^7 [BHC]
		Dynamics	BHCs	50	1	S/N ~ 50 per resolution element near 1 keV	40	2,000	Spectra, timing	0.5 to 40 keV		10 at 40 keV		Timing accuracy: 100 microseconds	3.0×10^7 [star]
		Equation of state	Neutron stars	75	1		80	6,000	Timing, spectra	0.25 to 10 keV	1,500 cm2 at 40 keV				1.2×10^{10} [XRB]
		Coronal heating, winds, convection zones, star formation	Stars	180	1-10**	Resolve Lithium-like and He-like lines	50	9,000	Spectra, timing, images	0.25 to 7 keV	1,000 cm2 at 0.25 keV		FOV of 2.5 arcmin at 1 keV		
		Planets, comets	Solar system objects	10		Phase resolved spectroscopy	40	400	Spectra, images	0.25 to 2 keV				10,000 counts per second per observatory	2.4×10^6 [comet]
								86,850 ksec (3 years)	Subsystem Requirements Tables (representative)	1-6, 1-8, 1-9	1-4, 1-6, 1-8, 1-9	1-6, 1-8, 1-9	1-3, 1-6, 1-8, 1-9, 2-1, 2-2	1-8, 1-11, 2-1	2-1, 2-4 Sect. 2.4.1.2, and Sect. 2.4.3

* Multiple pointings for monitoring observations.
** Multiple pointings for mappings.

Red numbers indicate driving requirements.

Data volume depends on source spectrum, brightness and integration time. Instrument conversions are XMS: 64 bits/photon, RGS: 48 bits/photon, HXT: 48 bits/photon.

stable orbit of the accretion disk), but many objects will be monitored on longer time scales, requiring repeat observations for an estimated total of about 9,000 ksec. Studying black hole evolution and general properties over a range of luminosities requires longer, single observations of approximately 150 fainter AGN of 50 ksec each for 7,500 ksec. In total, studies of supermassive black holes will require about 17,000 ksec.

1.2.3 Measurement Capabilities

The mission science objectives are fully supported by the baseline requirements summarized in Table 1-1. The baseline performance requirements can be traced in detail to the science objectives via Foldout 1. Additional mission requirements can be found in the TLRD. The performance margins are determined by comparison of the Reference Mission Performance with the baseline requirements. Note that some requirements are set at levels that already have been achieved on other X-ray missions (e.g., the angular resolution is met by XMM-Newton and exceeded by Chandra).

A preliminary set of minimum requirements has been assigned to the key measurement items to ensure a robust mission (Table 1-1). It has been noted that there is typically graceful degradation in science return as one approaches the minima (i.e., if there is a smaller field of view (FOV) more pointings can be utilized—though at the cost of fewer observations for a given mission lifetime).

Table 1-1: Key Measurement Capabilities

Measurement Parameter	Minimum Requirement	Baseline Requirement	Mission Goal	Reference Mission Performance	Margin
Bandpass (keV)	0.25 to 40	0.25 to 40	0.1 to 80	0.25 to 60 kev	20 keV
Effective Area (cm^2)					
0.25 keV to 10 keV	1,000 cm^2	1,000 cm^2	N/S	1,279 @0.25 kev	28%
1.25 keV	12,000 cm^2	15,000 cm^2	N/S	15,201 @1.25 kev	1%#
6.0keV	5,400 cm^2	6,000 cm^2	N/S	6,352 @6.0 kev	6%#
10 to 40 keV	1,200 cm^2	1,500 cm^2	N/S	4,990 @10 kev 1,542 @40 kev	230% 3%#
Spectral Resolving Power ($E/\Delta E$)					
0.25 to 6 keV	300	300	3000	991 @0.25 keV 354 @0.7 keV** 625 @1.25 keV	230% 17% 108%
				3000 @6 keV	100%
6 to 10 keV	1,200	1,500	3000		
				5000 @10 keV	1567%
10 to 40 keV	5	10	N/S		
				33 @40 keV	230%
Angular Resolution (HPD)					
<10 keV	15 arcsec	15 arcsec	5 arcsec	14.5 arcsec	4 arcsec (RSS)
>10 keV	1.2 arcmin	1 arcmin	20 arcsec	45 arcsec	39 arcsec(RSS)
Fields of View					
<10 keV	2 arcmin	2.5 arcmin	5 arcmin	2.5 arcmin	N/A*
>10 keV	4 arcmin	8 arcmin	10 arcmin	8 arcmin	N/A*
Bright Source Limit†	5,000 cps/beam	10,000 cps/beam	N/S	10,000 cps/beam	N/A
Absolute Timing (relative to UTC)	300 μsec	100 μsec	50 μsec	90 μsec	10 μsec

* Limited by detector format, not optics performance ** Overall system minimum resolution **N/S** = not specified
† No instrument damage occurs; at very high count rates, there is a gradual loss of spectral resolution
\# In general, optics designs and coatings are reference and are not yet optimized. Margins should improve significantly prior to Phase B.

1.2.4 Measurement Goals

Some parameters have goals (Table 1-1) that would increase mission capabilities with minimal increases in cost, schedule, or risk, and for which the technology appears achievable. The technology advances needed to achieve these goals will be part of the trades made during formulation, including consideration of impact on project resources. The science to be gained by reaching these goals is discussed below, but there would undoubtedly be many other gains, some that cannot yet be imagined.

High-Energy Bandpass: Extending the energy band beyond 40 keV will provide a longer lever arm for measuring the X-ray continuum in active galactic nuclei and, in particular, will better constrain the high-energy rollover in the Compton reflection signature from accretion disks and other Compton thick structures such as molecular tori, thus constraining the geometry of the X-ray reprocessor.

Spectral Resolving Power: Improving the spectral resolving power enables qualitative improvements in the ability to study more complicated plasmas, including photoionization features, turbulent velocities, tighter limits on gravitational smearing, and improvements in velocity diagnostics. Increasing resolution significantly also improves the detection capability for narrow absorption lines.

Angular Resolution: Improving the imaging capability of the SXT mirrors to ~5 arcsec half power diameter (HPD) allows observations of more crowded fields, achieves lower flux levels by lowering the confusion limit, and allows mapping of supernova remnants and galaxy clusters in greater detail.

1.2.5 Measurements and Data

X-ray astronomy instruments record a separate signal from every photon detected, unlike typical optical CCDs which need to integrate the signal from a number of photons to generate a detectable signal. As a result, X-ray data are stored event by event. This approach retains more information and allows greater flexibility of analysis. Every X-ray “event” (source photon or background cosmic ray) is characterized by a “pulse height” that encodes the energy of the incoming photon, arrival time, quality grade, and typically two position coordinates. The large amount of information for each event allows complex and sophisticated analysis. For example, a user may wish to exclude events that occurred during a period of high background and then display the events as a spectrum vs. time image. Retaining the individual events also retains the Poisson (“counting statistics”) nature of the data, and so allows the statistical significance of sources or features to be assessed more readily. The instantaneous data rate depends (nearly) linearly on the X-ray source brightness.

The science data products (Levels 1 and 2) derived from these “events” are X-ray spectra, images, and light curves (Foldout 1).

Level 1: Instrument-dependent corrections, such as the aspect solution, are applied. Level 1 data outputs are reversible (e.g., no photon event rejection). These products are sent to the observer.

Level 2: Takes Level 1 outputs and applies standard corrections. This includes filtering the event file on the good time intervals, cosmic ray rejection, and position transformation to celestial coordinates. A candidate source list and “finished” event file are produced, as well as a dispersed spectrum for grating data.

Level 3: Derives higher level information from the Level 2 outputs, including more precise source detection and characterization (fluxes, morphology), plus cross-correlation with source catalogs and X-ray line identification.

Data validation, analysis, and archiving are discussed in Section 2.4.3.

1.3 Mission Science Performance and Design

1.3.1 Instrumentation

Mission science performance requirements described in Section 1.2.1 are met using four identical observatories that orbit the L2 libration point (Foldout 2-E). All four observatories, activated by stored commands from the ground, view the same target at the same time. The timetagged data from the four observatories are combined on the ground for each observation to meet the top-level mission requirements. ***The observatories do not interact with each other or station keep with respect to one another, and communicate only with the ground.***

System Description: On each of the four Constellation-X observatories, the instrumentation is configured into a Telescope Module (TM).

Each TM consists of two types of telescope systems (Foldout 2-A):

- Spectroscopy X-ray Telescope (SXT) with bandpass from 0.25 keV to 10 keV
- Hard X-ray Telescope (HXT) with bandpass from 6 keV to 40 keV

The SXT uses a single Flight Mirror Assembly (FMA) shared by two instruments:

- Reflection Grating Spectrometer (RGS) with bandpass from 0.25 to 2.0 keV
- X-ray Microcalorimeter Spectrometer (XMS) with bandpass from 0.6 to 10 keV

The RGS and XMS combine to cover the SXT bandpass; the SXT and HXT together cover the mission bandpass. Overlap between systems provides cross calibration.

The SXT mirror, RGS, XMS, and HXT concept descriptions are provided in this section. Technology development efforts relevant to these systems are provided in Section 3. A description of the additional TM systems that provide the structural mounting and alignment, thermal control, calibration support, baffling, etc., is provided in Section 2.4.1.1.

Instrument Interfaces: The Constellation-X mirrors and instruments are modular, with clean and easily implemented interfaces to the observatory. Mechanical alignment tolerances to the TM are on the order of a millimeter in position and arcminutes in angular orientation. Kinematic mounts, similar to those used on dozens of flight missions, along with a stable structural and thermal design, assure that mechanical alignment tolerances are maintained over the mission life. Thermal interfaces between the instruments and observatory are generally passive with heaters, radiators, and heatpipes provided as necessary. The typical instrument science data rates are listed in Foldout 1.

Flowdown of Top-Level Mission Requirements: The following paragraphs discuss effective area, spectral resolving power, and angular resolution error budgets and requirements flowdown.

As shown in Figure 1-1, the XMS, RGS, and HXT instruments complement each other to meet the top-level mission effective area requirements across the mission bandpass. These effective area estimates are based on the full complement of mirrors and instruments from all observatories. A budget for the mission effective area, which allocates requirements to the telescope system components, is provided in Table 1-2. The current design includes modest margin between the predicted area and nominal top-level mission requirement. Further design optimization, alternate mirror coatings, and reduced structural blockage will improve these margins.

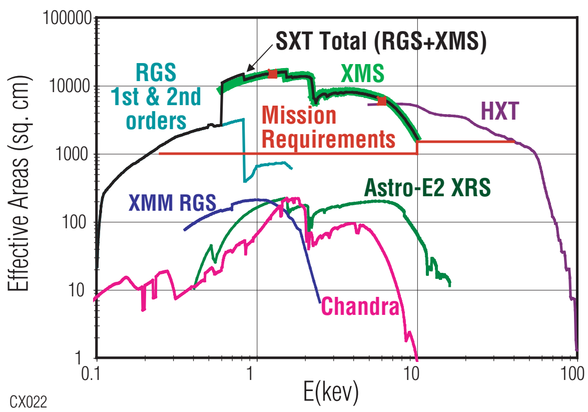


Figure 1-1: Mission Effective Area Curves

As shown in Figure 1-2, the XMS and RGS instruments complement each other to meet the top-level spectral resolution requirements

Table 1-2: SXT Effective Area Budget (Mission Total)

	Area At Energy		
	0.25 keV	**1.25 keV**	**6 keV**
SXT FMA Geometric Area	59,400	59,400	59,400
SXT FMA Losses			
–Reflectivity Loss	-17,118	-18,641	-50,691
–Structural Blockage	-5,919	-5,747	-1,472
–P-H Shell Alignment	-423	-611	-174
–Aperture Alignment	-211	-306	-87
–SXT Contamination - EOL	-423	-408	-87
SXT FMA Effective Area	35,305	33,687	6,889
Instrument/Telescope Losses			
–RGS Internal Vignetting	-784	-743	-51
–XMS(Cal QE, Filter, Fill Factor)	-19,628	-3,212	-394
–RGS(Grat Effy, CCD QE, Filter)	-12,659	-13,280	0
–Grating Internal Alignment	-157	-149	-10
–Off-axis Operation	-14	-172	-68
–Inst Contamination - EOL	-784	-941	-14
Total Area - Predicted	1,280	15,191	6,352
Total Area - Requirement	1,000	15,000	6,000
Margin (%)	28.0	1.3	5.9

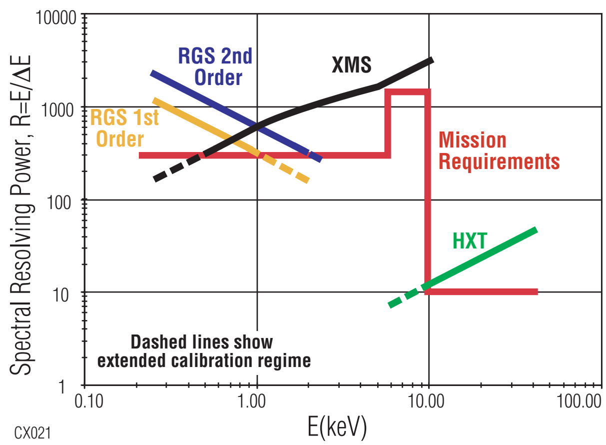


Figure 1-2: Mission Spectral Resolving Power vs. Energy

across the mission bandpass. The spectral resolving power R=E/ΔE of the RGS increases as energy decreases and meets or exceeds the resolving power requirements over the lower energy portion of the mission bandpass (0.25-1 keV). Since the energy resolution of the XMS is nearly constant (~2 eV), the XMS spectral resolving power increases with energy. The XMS is therefore the primary instrument from 1 to 10 keV. The HXT covers the bandpass above 10 keV.

The SXT angular resolution requirement is 15 arcsec (HPD). A preliminary angular resolution error budget is shown in Table 1-3. The SXT mirror on-orbit performance and telescope level effects are combined by root sum square (RSS) with instrument unique terms to show predictions and margins for the RGS and XMS SXT systems.

Number and Size of SXTs: Four SXT systems are baselined for the Constellation-X mission. This is a result of trade studies that considered the number of mission SXT systems (ranging from 1 to 12) and accounted for factors such as mirror fabrication and testing, launch vehicle throw mass and packaging, and number of instruments. Fewer SXTs have the advantage of fewer detectors but require larger diameter mirrors with longer focal lengths, which are more difficult to fabricate and test and require on-orbit deployable optical benches. With four SXTs, the mirror diameter of 1.6 m allows two systems to be packaged within a single 5 m-diameter launch vehicle fairing (Foldout 2-D); the focal length is 10 m, which can be accommodated by a fixed optical bench (OB) within an Atlas V fairing. Any advantages of more, smaller SXT mirrors are offset by the need for additional instrument detector systems, more extensive I&T, and additional launch vehicles, and do not offer any advantage in launch vehicle cost.

1.3.1.1 SXT Flight Mirror Assembly

The SXT FMA, illustrated on Foldout 3-E10, consists of four major components: the SXT mirror, the RGS Grating Array (RGA), and thermal pre- and post-collimators (see Section 2.4.1.1). X-rays enter the SXT FMA through the pre-collimator and are directed to a focus by the SXT mirror. The SXT mirror consists of highly nested reflectors utilizing a two-reflection Wolter Type I design, in which the incident X-rays reflect off confocal paraboloid and hyperboloid surfaces of revolution, at shallow angles. A schematic of the Wolter I concept is shown on Foldout 2-C. In the SXT design, the aperture is optimally filled with mirrors, facilitating high throughput of incident radiation. Approximately half the reflected X-rays pass through the RGA and impinge on the XMS at the telescope focus. The remainder are reflected or diffracted into various orders by the RGA and into the off-axis RGS Focal Plane Camera (RFC). All the X-rays pass through the thermal post-collimator en route to the focal plane.

SXT FMA Requirements: The requirements for the SXT mirror are listed in Table 1-4. These divide into top-level performance requirements and derived (engineering) requirements.

SXT FMA Implementation: The SXT mirror has adopted a segmented Wolter I approach for fabrication. The paraboloid and hyperboloid surfaces of revolution are composed of a number of segments of equal arc length. The segmented approach allows for a modular design amenable to mass production. It also obviates the need for very large reflector forming mandrels and mounting fixtures, the technical feasibility and cost-effective mass production of which are highly questionable. Table 1-5 lists SXT mirror key properties.

The nominal design for the mirror (Foldout 3-B9) consists of 18 modules, six identical inner modules subtending a 60-degree arc and 12 identical outer modules subtending a 30-degree arc. Each segment has two grazing incidence

Table 1-3: SXT Angular Resolution Error Budget (Arcsec)

	Item (HPD - arcsec)	Rqmt	Margin	Allocation/Predictions					Rationale
	RGS Resolution	15.00	4.01	14.46					4 satellites, post-processed
	Co-add 4 satellites				1.00				Superposition of data using X-ray centroids
	On-Orbit Telescope - single satellite				14.42				RSS
	CCD pixelization error					0.41			0.5 arcsec pixels
	• Grating resolution errors					5.00			Estimate
	XMS Resolution	15.00	4.95	14.16					4 satellites, post-processed
	Co-add 4 satellites				1.00				Superposition of data using X-ray centroids
	On-Orbit Telescope - single satellite				14.12				RSS
	• Calorimeter pixelization error					4.08			5 arcsec pixels
Common to XMS & RGS	• Telescope level effects					5.20			RSS
	– Image reconstruction errors (over obs)						4.24		RSS
	– SXT/Telescope mounting strain						2.00		Eng. estimate based on Chandra experience
	– SXT/SI vibration effects						2.00		Chandra experience (jitter)
	– SXT/SI misalignment (off-axis error)						1.00		Chandra experience
	– SXT/SI focus error						0.20		Analysis
	• SXT Optics - on-orbit performance					12.48			RSS
	– SXT Mirror launch shifts						2.00		Eng. est. based on Chandra
	– Thermal errors						2.24		RSS
	– Material stability effects						1.00		Est. based on Chandra work
	– SXT Mirror, as built						12.07		RSS
	--Gravity release							1.50	FEA analysis using vertical assy
	--Bonding strain							3.00	Eng. estimate, analysis in process
	--Alignment errors (using CDA)							3.38	RSS
	--Installation in housing							5.00	Est. based on OAP1 testing
	--Optical elements							9.90	Est. based on tech dev program

Legend: Requirement Margin RSS Prediction Allocation

reflection stages, referred to as primary (paraboloid), and secondary (hyperboloid).

Key components of the mirror include: (1) Reflectors, consisting of thermally formed glass substrates with an epoxy replicated reflecting surface (Foldout 3-A5). A gold overcoat provides high reflectivity in the 0.25-10 keV bandpass. The primary and secondary reflectors are separate pieces. Each outer module contains 90 reflector pairs, each inner contains 140; an SXT mirror has 3,840 reflectors. (2) Module housings, fabricated from a laminate consisting of carbon fiber composite and aluminum sheets, designed to match the coefficient of thermal expansion (CTE) of the reflectors. (3) A mounting plate, also CTE matched to the reflectors, which form an interface surface to the RGA. Each module, in turn, is incorporated in the FMA (Foldout 3-E).

Table 1-4: SXT FMA Requirements Per Observatory

SXT FMA Performance Requirements		Trace to Top-Level Mission Requirements Foldout 1
Bandpass	0.25 to 10 keV	Allocation of mission bandpass to SXT
Effective area (per mirror) @0.25 keV @1.25 keV @6 keV	 8,826 cm^2 8,421 cm^2 1,722 cm^2	Provides 33,000 cm^2 at 1 keV and 6,900 cm^2 at 6 keV for the mission. Allows effective area losses due to detector efficiency, etc., to achieve TLRD baseline requirement per error budget summarized in Table 1-2.
Angular resolution	12.5 arcsec HPD	Error budget allocation to mirror that allows telescope system to achieve requirement of 15 arcsec with 4 arcsec margin combined by RSS (Table 1-3)
Field of view	2.5 arcmin	Exceeds instrument FOV; defined by detector FOV
Derived Requirements: SXT Mirror		**Derivation**
Diameter	1.6 m	To meet mission area requirements with 4 mirrors
Focal length	10 m	Consistent with grazing angle requirements for 1.6 m diameter mirror
Axial length	<70 cm	To fit within envelope and meet fabrication considerations
Operating temperature	20±1° C nominal	Range is per allocation from SXT angular resolution error budget (Table 1-3); minimizes angular distortions imposed by temperature change to components. Operating temperature is determined by optics assembly temperature
Mass	642 kg	Current engineering estimate
Derived Requirements: SXT Grating: See Table 1-3		
Derived Requirements: Thermal Pre/Post collimators		
Temperature gradient	1° C across diameter 1° C axial	Allocation from SXT angular resolution error budget (Table 1-3); minimizes angular distortions imposed by temperature gradients
Mass	47 kg	Current engineering estimate

SXT Mirror Estimated Performance: The expected SXT mirror performance is consistent with the requirements for meeting mission measurement and investigation objectives.

Table 1-5: SXT Mirror Key Parameters

Parameter	Description
Design	Segmented Wolter I
Reflector substrate material	Thermally formed glass
Reflecting surface fabrication	Epoxy replication
X-ray reflecting surface	Gold
Number of nested shells	140 (inner); 90 (outer)
Total number of reflectors	3840
Reflector length	20-30 cm
Number of modules	6 (inner); 12 (outer)
Module housing composition	Composite/aluminum laminate, CTE-matched to substrate
Largest reflector surface area	0.16 m^2
Substrate density	2.4 gm/cm^3
Reflector thickness	0.4 mm
Reflector microroughness	0.4 nm RMS
FMA mechanical envelope	1.7 m dia x 1.65 m

Table 1-2 shows the overall SXT effective area vs. requirements. The predicted overall effective area at 1.25 keV is 15,200 cm^2. Based on the measured performance of the prototype components, it is anticipated that the SXT mirror will have an angular resolution of 12.5 arcsec, independent of energy, consistent with the error budget in Table 1-3. This anticipated value leaves a 4 arcsec performance margin. The angular resolution will not degrade appreciably across the instrument FOV.

SXT FMA Design/Flight Heritage and Development Items: Wolter I mirrors have been flown on Einstein, ROSAT, Chandra, and XMM-Newton. The multiple-nested, thin-walled reflector SXT design draws its significant heritage from the segmented, thin foil mirrors developed at GSFC. The reflecting surfaces of the foil mirrors have traditionally been conical approximations of the curved Wolter I surfaces. These mirrors flew on BBXRT, ASCA, Astro-E, and InFOCμS, and are being prepared for Astro-E2. The SXT design has technological overlap with the XMM-Newton mirrors, sharing similar concepts for mass production process and facility, and for multiply-nested thin, lightweight shells leading to comparable imaging performance. The SXT mirror development also exploits the extensive experience gained from Chandra and its predecessors, ROSAT and Einstein, in systems engineering and modeling, alignment, and thermal pre- and post-collimator design. Collimators are further discussed in Section 2.4.1.1.

1.3.1.2 Reflection Grating Spectrometer

The RGS is an array of co-aligned reflection gratings (RGA) and an array of back-illuminated (BI) CCD detectors (the RFC) that detect the X-rays reflected and dispersed by the RGA. The RGA, which consists of about 1000 individual gratings held in grazing incidence with respect to the local converging beam, works as a single dispersive optic. It focuses X-rays passing through the SXT onto the RFC in an "inverted Rowland circle" design (Foldout 2-C). The RGS block diagram is shown in Figure 1-3.

The RFC (Foldout 4-B12) uses two separate camera systems: the Spectroscopy Readout Camera (SRC) and the Zero Order Camera (ZOC). The SRC is a long, narrow strip of CCDs that images the dispersed spectrum from the gratings over the RGS bandpass while the ZOC reads out the image of the sky (the grating zero-order image) reflected off the gratings. The ZOC is required to anchor the spectrometer wavelength scale by tracking small aspect drifts on the sub-arcsec scale.

RGS Requirements: The RGS system performance requirements are provided in Table 1-6, along with the trace to the top-level mission requirements, and the derived requirements for the RGA and RFC. The RGS spectral resolution is driven by the SXT mirror angular resolution, resulting in a reflected requirement from the RGS onto the SXT angular resolution performance of 15 arcsec.

RGA Implementation: The RGA uses a modular approach. The thin gratings are aligned and assembled into grating subassembly modules, identical subgroups of gratings that are made up of about 10 gratings each (Foldout 3-D19).

The gratings are aligned with respect to one another and to reference surfaces on the module frames. The alignment fixturing disengages from the gratings after the gratings are bonded to the subassembly frame. These identical grating modules are in turn attached to the array

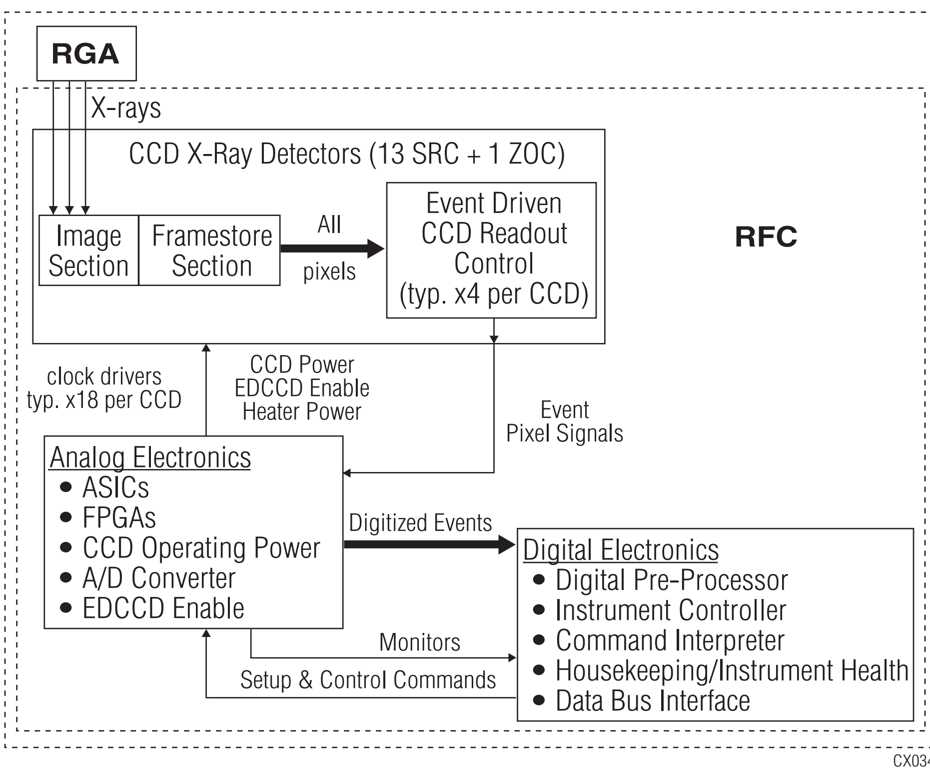


Figure 1-3: Block Diagram of the RGS System

Table 1-6: RGS Requirements Per Observatory

RGS Performance Requirements		Trace to Mission Top-Level Requirements (Foldout 1)
Bandpass	0.25-2.0 keV (6 to 50 Å)	In combination with XMS, meets spectral resolution rqmts over the 0.25 – 10 keV bandpass. 1 to 2 keV used for calibration with XMS
Spectral resolving power,R ($\lambda/\Delta\lambda$)	≥300 below 1 keV	Meets TLRD baseline requirement for R
Effective area @0.25 keV @0.6 keV @1.25 keV	 250 cm^2 625 cm^2 175 cm^2	Flowdown from mission baseline effective area requirement
Derived RGS Grating Array Requirements		**Derivation**
Grating efficiency: @0.25 keV (1st Order) @0.6 keV (1st Order) @1.25 keV (2nd Order)	 >0.14 >0.22 >0.06	Flowdown from area requirements. Theoretical efficiency with 50% margin. Met with 40% margin when measured efficiencies for anisotropically etched grating test ruling are used
Interception factor	0.57	Fraction of X-rays entering RGA intercepted by gratings and dispersed in the various orders. Flowdown from area requirements
Straight-through factor	0.38	See Inteception factor (above)
Grating goove parameters α: incidence angle γ: graze angle d: groove spacing	 α = 1.61 deg. γ = 2.21 deg. 1/d = 407 mm^{-1}	Given 15 arcsec HPD telescope, and requiring $\lambda/\Delta\lambda$=400 at blaze (blaze = 0.605 deg.) reflectivity is optimized there using scalar diffraction theory
Grating flatness	≤2 arcsec FWHM	Grating error budget flowdown for spectral resolution. Combined with alignment error, allows broadening of the line spread function core by no more than 30% and SXT mirror dominates
Grating to grating alignment	≤2 arcsec FWHM	See grating flatness item (above)
Mass	50 kg	Current engineering estimate
Derived RGS Focal Plane Camera Requirements		**Derivation**
Quantum efficiency @0.25 keV @0.6 keV @1.25 keV	 >0.86 >0.93 >0.98	Flowdown from area requirements
Energy resolution at 250 eV	> 90% events within 100 eV band	Required to separate spectra from overlapping orders. The requirement is met with 20% margin by state-of-the-art (ACIS-S) BI CCD's
Optical Blocking Filter -Visible light rejection -X-ray transmission @0.25 keV @1.25 keV	 >10^8 >0.8 >0.98	 Optical light rejection to avoid CCD pulse height confusion Flowdown from area requirements in conjunction with grating efficiency meets the top-level area requirements
Optical starlight rejection	≤1 electron/pixel/read-out for 10 magnitude star	Joint requirement on pre-collimator, SXT straylight performance, and SRC CCD optical blocking filter performance
Pixel size	24 μm	Required to critically sample the Point Respose Function
SRC number of pixels, dispersion direction	1.3 X 10^4	Required to cover the dispersed instrument bandpass (0.25 to 2 keV), given above pixel size and SXT focal length. (1024 pixels x 13 CCDs)
SRC number of pixels, cross-dispersion direction	512	Required to provide adequate areas to enable background subtraction
ZOC CCD format	1024 X 1024	Identical to SRC chips to minimize costs
Frame readout rate	2 second integration time per frame	< 50% pileup in central CCD pixel for bright source limit, assuming 20% flux in single emission line
Operating temperature	-60° C to -80° C	Reduces hot and flickering pixels
Mass	33 kg	Current engineering estimate

integrating structure to assemble the full grating array. Attachment to the integrating structure may be done by preparing precise receiving ends for the kinematic mounts built into the grating module frames or by aligning and bonding each grating subassembly. Table 1-7 shows the RGA design properties.

RFC Implementation: The CCD cameras that make up the RFC feature 13 backside illuminated CCDs with optical blocking filters applied directly on the thin insulating layer of the backside. CCDs in the Spectroscopy Readout Camera are mounted parallel to one another to form an approximate Rowland Circle (Foldout 4-B12). The CCDs' readout frequency is set to avoid X-ray event pileup, noisy pixels, and optical stray light. High frequency readout of the CCDs within the allowed power allocation is made possible by using "event drive" circuitry that involves a non-destructive charge sensor and a CCD "first-in, first-out" readout scheme where the significant pixels are diverted and eventually digitized (Foldout 4-B13). A block diagram of the RFC is provided within Figure 1-3.

Estimated RGS Performance: The effective area of the RGS instrument is shown in Figure 1-1. The predicted RGS effective area at 0.6 keV (including first and second spectral orders) exceeds its requirement by over 100%. The RGS significantly exceeds the mission requirement for resolving power R of 300 at lower energies.

RGS Design/Flight Heritage and Development Items: Mission requirements of the RGS will be met by using a design model with heritage from the reflection grating spectrometer instrument aboard XMM-Newton whose performance parameters are very similar to the Constellation-X RGS. The baseline design for the RGS is a scaled-up version of the existing grating spectrometer aboard XMM-Newton. The two XMM-Newton grating arrays each consist of 182 precision-aligned (2 arcsec), flat (2 arcsec), lightweight grating replicas of a single master grating. Approximately five times as many gratings will be required for each Constellation-X RGS, with a similar alignment budget. Consequently, the major development areas for the RGS lie in reducing the mass per unit mirror aperture area and improving fabrication processes for grating fabrication and CCDs. These areas of development are described in more detail in Sections 3.1.2 and 3.1.3.

Table 1-7: RGS Grating Array Parameters

Parameter	Description
Design	Reflection grating positioned on Rowland circle
Grating substrate material	Slumped glass or silicon wafer
Substrate density	2.4 g cm^{-3}
X-ray reflecting surface	Gold
Number of gratings per module	~10
Number of grating modules per assembly	100
Grating area (per grating)	100 x 200 mm
Grating thickness	< 0.9 mm
Module housing composition	Beryllium or graphite epoxy

1.3.1.3 X-ray Microcalorimeter Spectrometer

The XMS (Foldout 4-A) uses an X-ray microcalorimeter to sense individual X-ray photons as heat[16] and determine their energy with high precision (Figure 1-4). The unique feature of the microcalorimeter is that it combines very high spectral resolution with high quantum efficiency over a broad energy band in a nondispersive spectrometer. Thermodynamic limits determine the spectral resolution and drive the need for operation at a temperature below ~0.1 K. Although extraordinarily cold, such temperatures can be readily

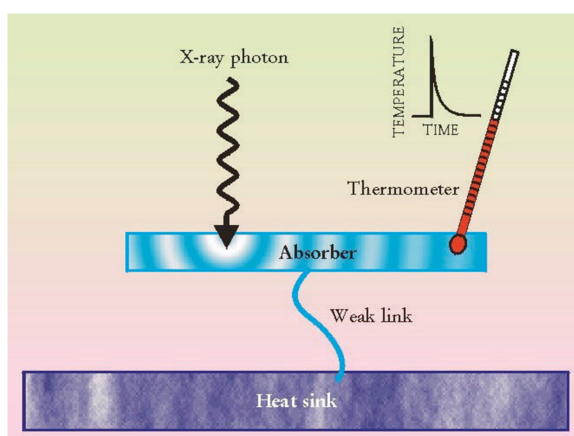


Figure 1-4: Conceptual Diagram of an X-ray Microcalorimeter

achieved and maintained using flight proven techniques.

XMS Requirements: The science requirements on Constellation-X specified in Section 1.2.1 require an X-ray spectrometer with very high resolving power (>1000) and nearly 100% intrinsic quantum efficiency over a ~10 keV energy bandpass, and rapid response time. The field of view and spatial resolution must be sufficiently high to spatially resolve an extended structure larger than the HPD of the SXT mirror without loss of spectral resolution. These requirements can only be achieved with an X-ray microcalorimeter array. Specific performance requirements are given in Table 1-8.

XMS Implementation: A block diagram of the XMS is shown in Figure 1-5 and the key technologies are shown in Foldout 4-A. The reference design consists of a 32 x 32 array of superconducting Transition Edge Sensors (TES) based on microcalorimeters. The TES pixels are read out using Superconducting Quantum Interference Device (SQUID) amplifiers. There will be first-stage SQUID transformers coupled to each pixel, and these will in turn be coupled and multiplexed to a smaller number of second-stage SQUIDs. The second-stage SQUIDs will actually be series SQUID arrays for amplification and coupling to the external electronics. Surrounding five sides of the detector housing will be an active

Table 1-8: XMS Performance Requirements

XMS Performance Requirement		Trace to Top-Level Mission Requirements (Foldout 1)
Bandpass	0.6 – 10 keV	TLRD
Spectral resolving power ($E/\Delta E$)	1500 at 6 keV	TLRD
Angular resolution	5 arcsec	Oversample SXT PSF by a factor of 3
Field of view	2.5 arcmin	TLRD
Derived Detector Requirements		**Derivation**
Pixel size	242 µm	Meets TLRD beam sampling requirement
Number of pixels	32 x 32	Gives 2.7 arcmin FOV vs. 2.5 arcmin requirement
Energy resolution	4 eV at 6 keV; 2 eV at 1 keV	Gives $E/\Delta E$ = 1500 at 6 keV
Intrinsic quantum efficiency	95%	Flowdown to meet effective area req.
Detector speed	<300 µsec pulse decay time constant	Supports bright source counting rate req.
Time resolution	10 µsec	Allocation to meet absolute timing req.
Derived CADR Requirements		**Derivation**
Detector stage temperature	0.050 – 0.070 K	Required to achieve detector energy resolution
Temperature stability	~2 µK RMS from 1 Hz to 2 kHz	Base temperature of array must be maintained so as not to change detector response
Cooling power	6 µW for array stage 1 mW for “1 K” stage	Based on estimated heat load into detector stage and heat sink for 2nd stage SQUIDs
Derived Cryocooler Requirements		**Derivation**
Cooling power	20 mW at 6 K	Cryocooler cooling power based on overall CADR system design requirements
Lifetime	Same as overall mission	No consumables are being considered for the baseline
Derived Instrument Requirements		**Derivation**
Mass	147 kg	Current engineering estimate
Power (watts)	80/146 (min/max) 150/200 (BOL/EOL)	For analog, digital, CADR control electronics Cryocooler electronics
Data rate (avg/peak)	7.2/640 kbps	Average source rate plus 840 bps H/K data Peak rate from bright sources limit

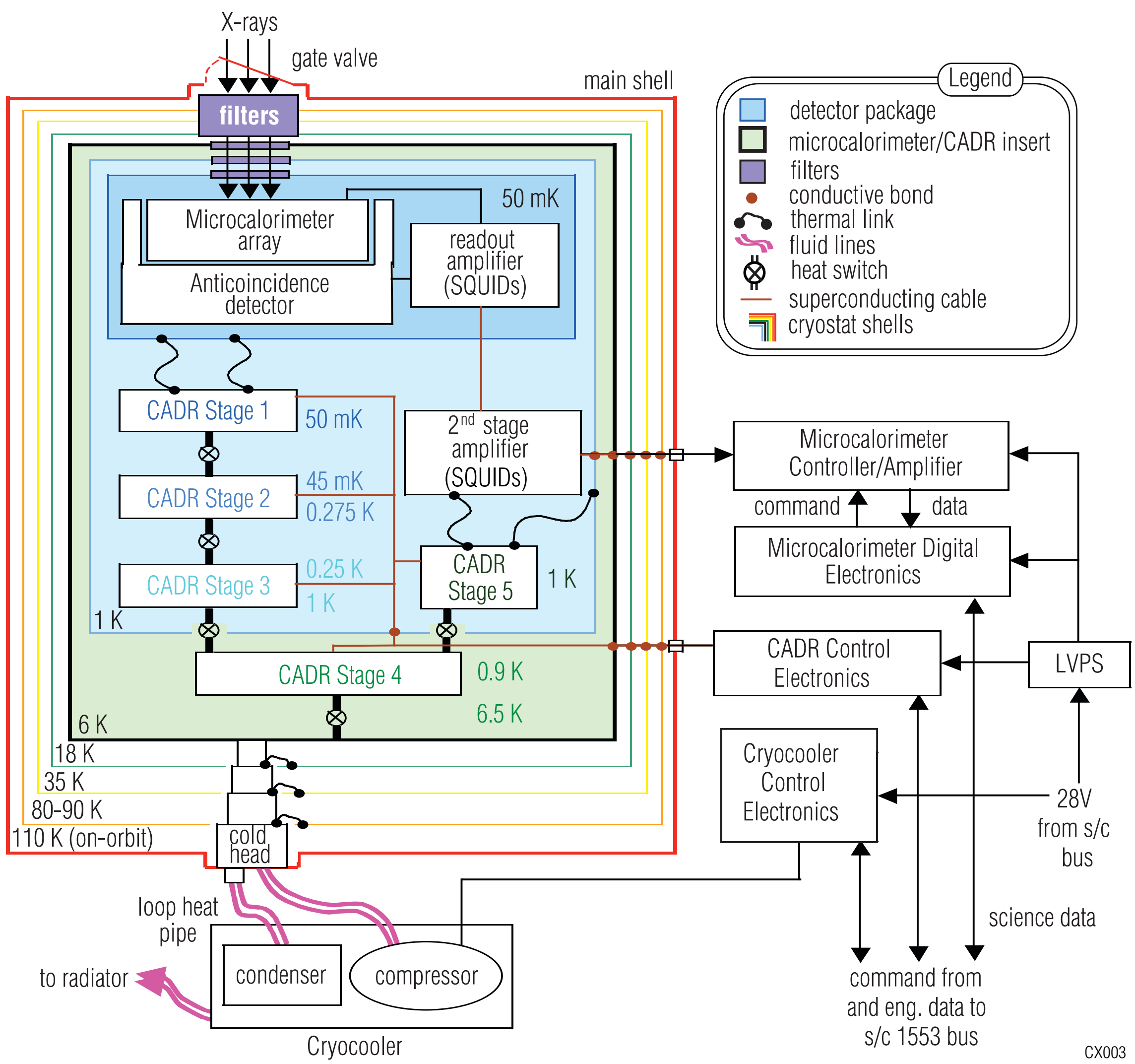


Figure 1-5: XMS Instrument System Block Diagram

anticoincidence detector, based on a thermal detector, sensitive to ballistic photons produced by charged particles. This will also be read out with SQUID amplifiers to simplify the design of the detector. Such detection schemes are typically used in ground-based dark matter searches[17].

The XMS cooling system (consisting of the CADR and cryocooler) has no stored cryogens, thus maximizing the lifetime/mass ratio for the instrument. Cooling of the detector stage will be achieved using a multistage CADR (Foldout 4-A10), which provides the necessary cooling power down to 50 mK. The warmer stages of the CADR are sequentially linked through heat switches and then cycled to transfer heat to the relatively warm cryocooler interface. The intermediate temperatures will be set during Phase B by trade studies involving the blocking filters, series SQUID arrays, and CADR efficiencies. The final operating temperature of the series SQUID arrays will be determined as the system design of the TES, CADR, cryocooler and cryostat matures.

A mechanical cryocooler will provide the 6 K heat sink for the CADR and will actively cool several thermal shields within the cryostat (Foldout 4-A9). It will also thermally anchor internal XMS signal and CADR current leads. The cryostat will provide the necessary structural support and thermal isolation for all microcalorimeter, CADR and cryocooler components contained within the outer shell.

Blocking filters in the aperture of the cryostat prevent heating of the detector stage by non-X-ray radiation. Transmission of these filters determines the low energy limit to the bandpass (~0.25 keV). The high-energy limit (>10 keV) is determined by the X-ray absorption efficiency of the absorber and the SXT mirror reflectivity. The X-ray photons are amplified, demultiplexed, triggered, and then analyzed for pulse height, arrival time, and anticoincidence with the analog and digital electronics external to the cryostat. The cryostat will have a one-time use aperture door that will be opened after launch after outgassing levels are adequately low (typically 2-3 weeks).

The XMS will be calibrated based on the Astro-E/E2 model. X-ray monochromotors will be attached to the XMS cryostat and used to measure the energy gain and spectral redistribution function over a wide range of instrument operating parameters. They will also be used to measure the X-ray transmission of the X-ray blocking filters.

Estimated XMS Performance: The baseline XMS design meets the basic performance requirements listed in Table 1-8. At 6 keV, the overall quantum efficiency is determined by the filling factor of the array. This works out to 95% with 6 μm gaps between pixels (8 μm has already been demonstrated (Foldout 4-A). At lower energies, the transmission of the blocking filters determines the efficiency, and transmissions have been adopted based on Astro-E2-like aluminized-polyimide designs. The overall effective area of the XMS/SXT is shown in Figure 1-2 and meets the baseline requirements.

Single-pixel TES devices with a resolution of 2-4 eV at 1.5 keV have already been demonstrated, and a resolution of about 4 eV has been demonstrated[18] in a TES at 6 keV. Microcalorimeters with semiconducting thermometers (ion-implanted Si or neutron transmutation-doped Ge) have achieved 4-6.8 eV[19]. These values meet the baseline requirements of Table 1-1. An energy resolution of 1.9 eV is possible for an ideal TES detector with T_c = 100 mK, heat sunk to 50 mK and meeting the Constellation-X requirements for pixel geometry and efficiency. Real devices have additional noise that seems to behave in a manner dependent on the device fabrication process. This indicates that it should be possible to reduce this noise component through systematic device engineering and optimization. Progress in this field has been extremely encouraging, and it is anticipated that a resolution of 2 eV at 6 keV will be achieved. Thus, the key development area for the XMS is producing large, close-packed arrays of microcalorimeters with this level of performance.

Technology Heritage and Development Items: Microcalorimeter spectrometers have been developed for space applications for an orbiting observatory[20] (the Astro-E2 high resolution X-ray Spectrometer [XRS]) and two successful suborbital flights[21], the X-ray Quantum Calorimeter (XQC), as well as numerous ground-based instruments. Under construction for a launch in February 2005, Astro-E2 will replace the original Astro-E observatory that was lost during launch in February 2000. Figure 1-6 depicts an actual 36-element flight microcalorimeter array from the Astro-E2 XRS program. Four support beams for each pixel provide thermal isolation and electrical readout (for clarity, the image shows the array prior to absorber attachment; the pixel pitch is 640 microns). The relevance to Constellation-X is that many of the XMS component technologies take their heritage from the designs and flight qualification processes of these programs.

The technology required for the XMS is rooted in extensive space flight development programs at GSFC. XRS and XQC instruments use pixel arrays based on semiconductor thermometers and cooled to 60 mK with single-stage CADRs in cryogenic systems

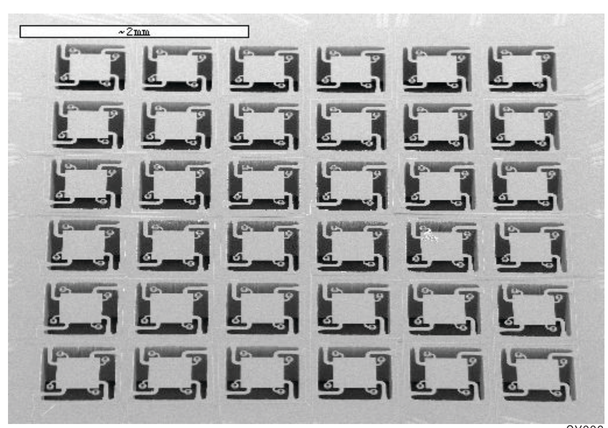


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Figure 1-6: Actual flight qualified X-ray microcalorimeter array from Astro-E2 XRS. Shown prior to absorber attachment.

designed to survive the demanding loads of solid rocket launch vehicles. Based on pre-launch thermal balance tests, the XRS He dewar achieved its demanding requirement of < 1.2 mW total heat load with 30% margin[22]. Digital signal processing with optimal filtering has been developed and used onboard these instruments to achieve maximal spectral resolution with minimum telemetry downlink.

The SQUIDs required for readout have also been fabricated at the National Institute of Standards and Technology (NIST). Although these must be further developed and subjected to space environmental testing, SQUID amplifiers have been successfully flight-qualified under the Gravity Probe B program and a Space Shuttle experiment[23].

The aperture door mechanism will be a spring-loaded pyro-activated design based on the Astro-E/E2 units.

The first space flight Adiabatic Demagnetization Refrigerator (ADR) was developed and qualified for the XRS instrument. An identical unit is presently being built for the Astro-E2 reflight. The design is also the basis for two nearly identical ADRs for two SOFIA instruments (HAWC and SAFIRE) that have been fully tested and delivered. The University of Wisconsin, in collaboration with the GSFC, has successfully operated an ADR in zero-g on its suborbital instrument, the XQC. To date, there have been two successful launches of the XQC, with the ADR maintaining stable operation at 60 mK each time.

Fundamental cryocooler technologies exist in flight coolers employed on HST/NICMOS, AIRS, and TES reaching temperatures down to 50 K. Manufacturers of these coolers have laboratory versions that reach lower temperatures, and they are now involved in the development of the needed 6 K cryocoolers.

1.3.1.4 Hard X-ray Telescope

The HXT on each observatory consists of three highly nested, multilayer-coated, grazing incidence mirror assemblies, each of which focuses onto a separate hard X-ray detector. Multiple, modest diameter mirror assemblies provide shallow graze angles, maximizing the reflectivity at energies above 10 keV. Depth graded multilayer coatings on the mirrors further increase the bandpass and FOV over that achievable with standard metal coatings. The HXT is coaligned with the SXT to ensure that both telescopes view the same target. Figure 1-7 shows a block diagram of the HXT.

HXT Requirements: Table 1-9 summarizes the HXT requirements, traced to the top-level science requirements.

Implementation: Each mirror assembly consists of a nested set of approximately 150 shells in a conical approximation of a Wolter-I geometry. In the reference implementation, each shell is divided into six segments in azimuth and four segments along the optical axis, for a total of 24 segments per shell. Table 1-10 lists the HXT mirror parameters.

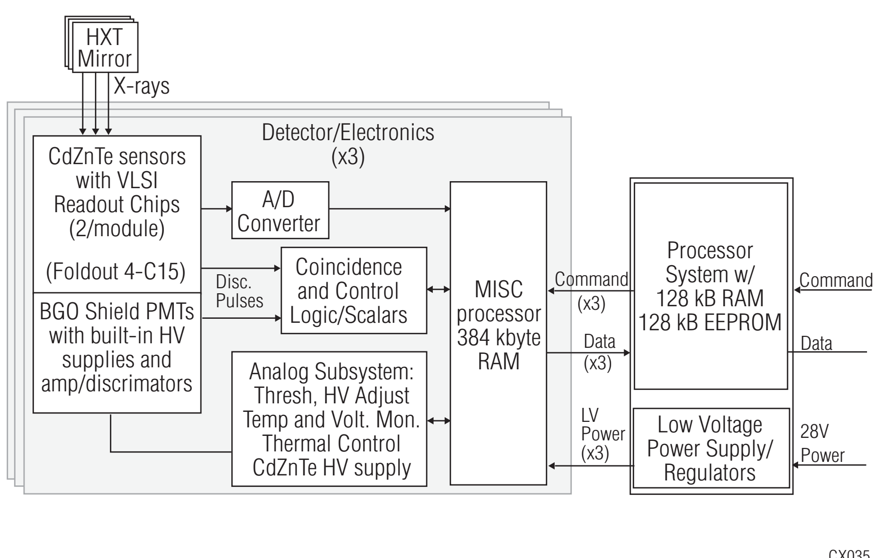

Figure 1-7: Block diagram of the HXT system

Table 1-9: HXT Requirements Per Observatory

HXT Performance Requirements		Trace to Top-Level Mission Requirements
Bandpass	6 to 40 keV	Allocation of mission TLRD band pass to HXT; provides calibration with SXT from 6 to 10 keV
Spectral resolving power (E/ΔE)	10	Meets baseline mission requirement for R, for 10 keV and above
Angular resolution	<1 arcmin HPD	Meets baseline mission angular resolution requirement for 10 keV and above
Signal/background	$\geq$1 for T< 2 x 10^4 sec	
Field of view	$\geq$8 arcmin	Meets mission FOV for 10 keV and above
Mass	151 kg	Current engineering estimate
Derived HXT Mirror Requirements		**Derivation**
Focal length	10 m	Provides shallow graze angles for high-energy
Diameter	40 cm	
Collecting area	625 cm^2 for each mirror (7500 cm^2 for mission)	Is requirement
Derived HXT Detector Requirements		**Derivation**
Pixel size	500 micron	Corresponds to 10 arcsec; oversamples by a factor of 6
Number of pixels	28 x 48	2 hybrids per focal plane
Quantum efficiency	0.90	
Operating temperature	-15° C to -5° C	

The reflectors are fabricated by thermally forming thin glass sheet into cylindrical segments of approximately the correct radius. These segments then undergo an epoxy replication step against a polished conical mandrel to remove mid-frequency figure errors. The segments are then coated with a depth-graded W/Si multilayer structure in a magnetron sputtering chamber (Foldout 3-C12). The segments are characterized for reflectance and mounted into the mirror.

Table 1-10: HXT Mirror Parameters

Parameter	Description
Design	Segmented Wolter I conical approximation
Substrate material	Thermally formed glass
Reflecting surface fabrication	Epoxy replication
X-ray reflecting surface	W/Si graded multilayer
Number of nested shells/mirror	150
Number of reflectors/mirror	1800
Reflector length	12 cm
Number of azimuthal segments	6
Largest reflector surface area	250 cm^2
Outer, inner mirror radius	6, 20 cm
Substrate density	2.4 g cm^{-3}
Reflector thickness	0.3 mm
Reflector roughness (RMS)	0.3 nm

The mounting process begins with a central mandrel, which serves as a base and also to locate and align the final mirror assembly in the OB. Using a custom assembly machine, glass segments for a shell are laid down, and graphite spacers epoxied to the back (Foldout 3-C11). The spacers are then machined to the desired surface, and the next shell is laid. This method constrains the segments to the desired final radius and eliminates stackup error.

The focal plane for each mirror assembly contains a high-Z, wide bandgap semiconductor (CdZnTe or CdTe) detector readout by a custom, low-noise ASIC. The detector is hybridized: the anode contact is segmented into pixels (Foldout 4-C15, insert), with each pixel bump bonded to a separate readout channel on the ASIC chip. The pitch of readout circuits matches that of the contacts on the sensor. Due to size limitations on the readout and sensors, each focal plane will contain two hybrids mounted side-by-side on a board (Foldout

Table 1-11: HXT Detector Parameters

Parameter	Description
ΔE (FWHM)	<1.2 keV (6 keV)
Dimension	2.3 x 2.3 x 0.2 cm
Bits/photon	48
Max. count-rate	50 cts/sec/pixel 200 cts/sec/module
Typical count-rate	5 cts/sec/module
Time resolution	10 microseconds

4-C15). Table 1-11 summarizes the detector parameters. The 500 μm detector pixel size corresponds to 10 arcsec at the focal plane, meeting the top-level oversampling requirement. Each module (two hybrids) is supported by a Minimal Instruction Set Computer (MISC) processor situated on a board immediately behind the detectors. This processor controls readout of the ASIC and other external logic functions.

Because the HXT operates at high X-ray energies, where detector background dominates over diffuse emission from the sky, the HXT requires an active anti-coincidence shield to reject particle and locally produced photon backgrounds. The shield will be fabricated from an active inorganic scintillator (BGO or CsI), and will be configured in a well geometry, with the detector at the bottom. Determination of the geometry is awaiting detailed calculations of the background environment in the Constellation-X orbit.

Absolute HXT calibration will be largely performed in flight using cosmic sources. Routine gain stabilization will be accomplished using a pulser built into the ASIC and by small, radioactive ^{241}Am sources placed inside each anticoincidence shield.

Estimated HXT Performance: The configuration described above meets HXT performance requirements as listed in Table 1-9. Figure 1-1 shows a calculation of the effective area for the baseline, which exceeds the required 1500 cm^2 below 40 keV and has sensitivity extending to 60 keV. The HXT angular resolution performance prediction of 43.5 arcsec meets the requirement of 60 arcsec with significant (41 arcsec RSS) margin. This performance estimate is supported by a detailed error budget similar to the one developed for the SXT (see Table 1-3).

HXT Design/Flight Heritage and Development Items: HXT optics technologies are extrapolations of systems developed for balloon experiments. All principal fabrication steps for HXT optics have been demonstrated. Glass segments have been produced with multilayers of the required design and the reflectance demonstrated as high enough to meet the requirement. Segments have been mounted with sufficient precision to exceed the angular resolution goal, and prototype units have demonstrated that 45 arcsec resolution can be achieved with unreplicated shells on the outer radii (Foldout 3-C14). It remains to be demonstrated that replicated shells will meet resolution requirement at small radii, although modeling indicates that this will not be a major obstacle. In addition, the throughput due to obscuration must be improved to meet the HXT specification, and a prototype unit must be tested in the relevant environment.

The detectors (pixel sensor and custom low-noise electronics) have been developed for the HEFT balloon program, and will be demonstrated in flight in Fall 2003. The CdZnTe sensor material will soon have flight heritage from the Swift experiment and has been flown on at least five balloon experiments, including InFOCμS and EXITE. Flight-sized detectors have been fabricated and tested and currently meet the spatial resolution, count rate, spectral resolution, and quantum efficiency requirements. Further development of the ASIC is required to meet the low-energy threshold requirement (to allow cross-calibration with the XMS), and the packaging and interconnects currently are not space-qualified.

1.3.2 Mission Approach

The mission approach is addressed in Section 2. In particular, observatory and operations performance requirements are presented in Table 2-1 and Section 2.1. The mission operations concept is discussed in Section 2.3. Data validation, analysis, and archiving are discussed in Section 2.4.3.